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Solar dryer with thermal energy storage systems for drying agricultural food products: A review

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A B S T R A C T

Developing efficient and cost effective solar dryer with thermal energy storage system for continuous drying of agricultural food products at steady state and moderate temperature (40–75 °C) has become potentially a viable substitute for fossil fuel in much of the developing world. Solar energy storage can reduce the time between energy supply and energy demand, thereby playing a vital role in energy conservation. The rural and urban populations, depend mainly, on non-commercial fuels to meet their energy needs. Solar drying is one possible solution but its acceptance has been limited partially due to some barriers. A great deal of experimental work over the last few decades has already demonstrated that agricultural products can be satisfactorily dehydrated using solar energy. Various designs of small-scale solar dryers having thermal energy storage have been developed in the recent past, mainly for drying agricultural food products. Therefore, in this review paper, an attempt has been taken to summarize the past and current research in the field of thermal energy storage technology in materials as sensible and latent heat in solar dryers for drying of agricultural food products. With the storage unit, agricultural food materials can be dried at late evening, while late evening drying was not possible with a normal solar dryer. So that, solar dryer with storage unit is very beneficial for the humans and as well as for the energy conservation.

Contents

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Nomenclature

a_m	fraction melted
a_r	fraction reacted
C_{ap}	average specific heat between T_i and T_f (J/kg K)
C_{lp}	average specific heat between T_m and T_f (J/kg K)
C_p	specific heat (J/kg K)
C_{sp}	average specific heat between T_i and T_m (kJ/kg K)
Δh_m	heat of fusion per unit mass (J/kg)
Δh_r	endothermic heat of reaction
m	mass of heat storage medium (kg)
Q	quantity of heat stored (J)
T	temperature (°C)
T_f	final temperature (°C)
T_i	initial temperature (°C)
T_m	melting temperature (°C)

1. Introduction

Drying is an essential process in the preservation of agricultural products. Food products, especially fruits and vegetables require hot air in the temperature range of 45–60 °C for safe drying. Drying under controlled conditions of temperature and humidity helps the agricultural food products to dry reasonably rapidly to a safe moisture content and to ensure a superior quality of the product [1]. Controlled drying is practiced mostly in industrial drying processes. Hot air for industrial drying is usually provided by burning fossil fuels, and large quantities of fuels are used worldwide for this purpose. High cost of fossil fuels, gradual depletion of its reserve and environmental impacts of their use have put severe constraints on their consumption. Many rural locations of developing countries suffer from non-access to grid electricity; supplies of other non-renewable sources of energy are also either unavailable, unreliable or, for many farmers, too expensive. In such areas, crop-drying systems that employ electrically operated fans, heaters and other accessories are inappropriate. The large capital and running costs of fossil fuel-powered dryers are often not affordable for small farmers.

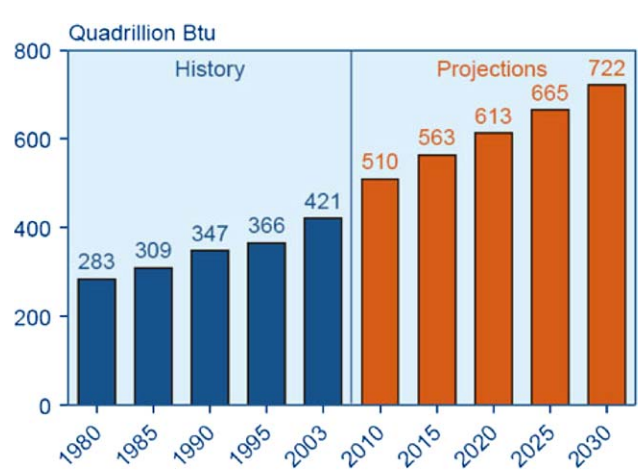

Fig. 1. Showing World marketed energy consumption, 1980–2030.*Source*: IEO2006 [2].

According to the International Energy Outlook 2006 [2], total World marketed energy consumption grows from 421 quadrillion British thermal units (Btu) in 2003 to 563 quadrillion Btu in 2015 and 722 quadrillion Btu in 2030 on an average by 2.0% per year shown in Fig. 1 and India is the fifth largest energy consumer, Fig. 2 [3]. Energy consumption for drying in developing countries is a major component of the total energy consumption, including commercial and non-commercial energy sources. Utilization of solar energy for thermal applications, like cooking, heating and drying, is well recognized in tropical and semitropical regions. Harnessing solar energy for drying offers significant potential to dry agricultural products such as food grains, fruits, vegetables and medicinal plants, thereby eliminating many of the problems experienced with open-sun drying and industrial drying, while saving huge quantities of fossil fuels. Various drying techniques are employed to dry different food products. Each technique has its own advantages and limitations. Industrial drying offers quality drying whereas its high cost limits its use. Open-sun drying suffers from quality considerations though it enjoys cost advantage. A solar air heater provides the hot air with a large variation in the temperature to the dryer only during sunshine hours. Whereas, drying of many agricultural products (e.g. cereals, pulses, foods and vegetables) are performed at the steady and moderate temperature and continuously for few days. In such a case, the thermal storage is required with a solar air heater for continuous drying so that possibility of drying during partial clouds and/or in late evening hours continuously for few days and hence, the storage will increase the utility and reliability of the solar dryers. A thermal storage unit integrated with the solar air heater may be charged during the peak sunshine hours and utilized (discharged) during off-sunshine hours for supplying the hot air to the dryer. The performance of solar air heaters has been simulated, designed, tested and suggested by many researchers for crop-drying purposes [4–9]. Choosing the right drying system is thus important in the process of drying agricultural products. Especially, in the tropical regions, where some crops have to be dried during rainy season, special care must be taken in choosing the drying system.

India is blessed with good sunshine. Most parts of the country receive mean daily solar radiation in the range of 5–7 kWh m^{-2}, and have more than 275 sunny days in a year [10]. Hence, solar drying has a high potential of diffusion in the country, and offers a viable option in the domestic sector. It is identified as an appropriate technology for Indian masses, and has numerous advantages such as no recurring costs, potential to reduce drudgery, high nutritional value of food, high durability, etc. In spite of these advantages, the main hurdles in its dissemination are reluctance to acceptance as it is a novel technology, intermittent nature of sunshine, limited space availability in urban areas, higher initial costs and convenience issues [11].

Solar energy is free, environmentally clean, and therefore is recognized as one of the most promising alternative energy recourses options. In near future, the large-scale introduction of

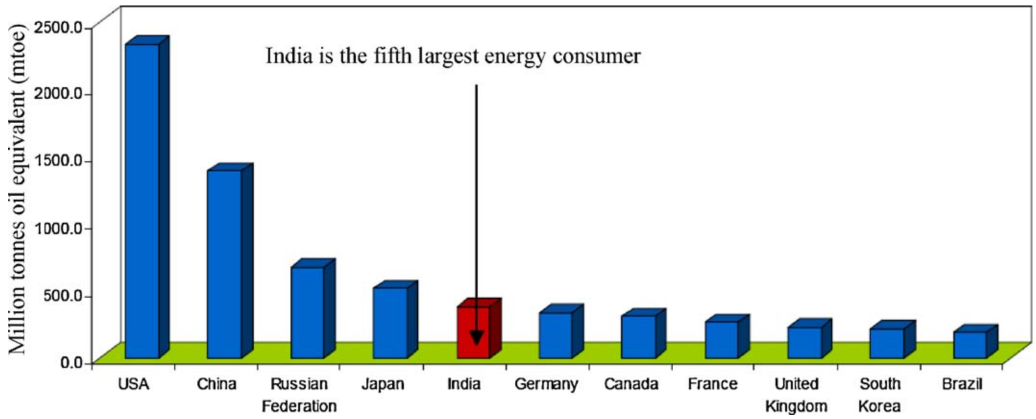

Fig. 2. Showing India's energy scenario.*Source*: BP States [3].

solar energy systems, directly converting solar radiation into heat, can be looked forward. However, solar energy is intermittent by its nature; there is no sun at night. Its total available value is seasonal and is dependent on the meteorological conditions of the location. Unreliability is the biggest retarding factor for extensive solar energy utilization. Of course, reliability of solar energy can be increased by storing its portion when it is in excess of the load and using the stored energy whenever needed. Energy storage is, therefore, essential to any system that depends largely on solar energy. It adjusts temporal mismatches between the load and the intermittent or variable energy source, thereby improving the system operability and utility. Solar radiation cannot be stored as such, so first of all an energy conversion has to be brought about and, depending on this conversion, a storage device is needed. Solar energy can be stored by thermal, electrical, chemical, and mechanical methods.

2. Thermal energy storage

Energy storage is a key issue to be addressed to allow intermittent energy sources, typically renewable sources, to match energy supply with demand. There are numerous technologies for storing energy in various forms including mechanical, electrical and thermal energy [12]. Thermal energy can be stored in well-insulated fluids or solids as a change in internal energy of a material as sensible heat, latent heat and thermo-chemical or combination of these. An overview of major technique of storage of solar thermal energy is shown in Fig. 3 [13].

2.1. Sensible heat storage

In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid, utilizing the heat capacity and change in temperature of the material during the process of charging and discharging. The amount of heat stored depends on the specific heat of the medium, the temperature change and the amount of storage material [14].

$$Q = \int mC_p dT = mC_{ap}(T_f - T_i) \qquad (1)$$

The sensible heat storage capacity of some selected solid–liquid materials is shown in Table 1 [15]. Water appears to be the best SHS liquid available because it is inexpensive and has a high specific heat. However molten salts, oils and liquid metals, etc. are used above 100 °C. Rock bed type storage materials are used for air heating applications.

2.2. Latent heat storage

Latent heat storage (LHS) is the heat absorption or release when a storage material undergoes a change of phase from solid to liquid or liquid to gas or vice versa at more or less constant temperature

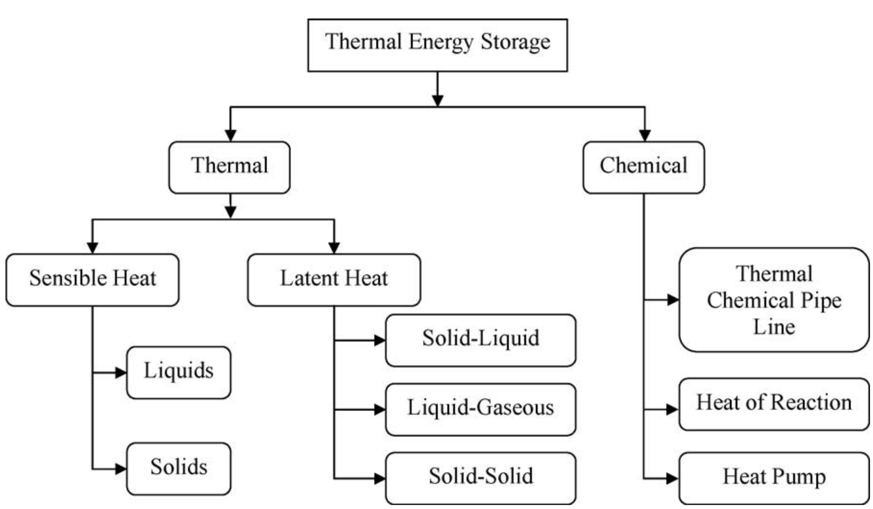

Fig. 3. Different types of thermal storage of solar energy.

Table 1
A list of selected solid–liquid materials for sensible heat storage.

Medium	Fluid type	Temperature range (°C)	Density (kg/m^3)	Specific heat (J/kg K)
Rock		20	2560	879
Brick		20	1600	840
Concrete		20	1900–2300	880
Water		0–100	1000	4190
Caloriea HT43	Oil	12–260	867	2200
Engine oil	Oil	Up to 160	888	1880
Ethanol	Organic liquid	Up to 78	790	2400
Propanol	Organic liquid	Up to 97	800	2500
Butanol	Organic liquid	Up to 118	809	2400
Isobutanol	Organic liquid	Up to 100	808	3000
Isopentanol	Organic liquid	Up to 148	831	2200
Octane	Organic liquid	Up to 126	704	2400

Source: Sharma et al. [15].

which is presented graphically in Fig. 4 [16]. The storage capacity of the LHS system with a phase change material (PCM) medium [14] is given by

$$Q = \int_{T_i}^{T_m} mC_p dT + ma_m \Delta h_m + \int_{T_m}^{T_f} mC_p dT \quad (2)$$

$$Q = m[C_{SP}(T_m - T_i) + a_m \Delta h_m + C_{lP}(T_f - T_m)] \quad (3)$$

2.3. Thermo-chemical energy storage

Thermo-chemical systems rely on the energy absorbed and released in breaking and reforming molecular bonds in a completely reversible chemical reaction. In this case, the heat stored depends on the amount of storage material, the endothermic heat of reaction, and the extent of conversion.

$$Q = a_r m \Delta h_r \quad (4)$$

Amongst above thermal heat storage techniques, latent heat thermal energy storage is particularly attractive due to its ability to provide high-energy storage density per unit mass and per unit volume in a more or less isothermal process, i.e. store heat at constant temperature corresponding to the phase-transition temperature of phase change material.

3. Benefits of LHS systems in comparison with SHS systems

(i) In LHS systems the temperature of the medium remains more or less constant since it undergoes a phase transformation.
(ii) Phase change storages with higher energy densities are more attractive for small storage.
(iii) PCMs absorb and emit heat while maintaining a nearly constant temperature.
(iv) They store 5–14 times more heat per unit volume than sensible storage materials such as water, masonry, or rock (Fig. 5 [17] and Fig. 6).
(v) Thermal storage capacity per unit mass and unit volume for small temperature differences is high.
(vi) Thermal gradients during charging and discharging are small.
(vii) Simultaneous charging and discharging is possible with appropriate selection of heat exchanger.

Phase change can be solid–solid, solid–liquid, solid–gas, liquid–gas and vice versa. In solid–solid transitions, heat is stored as the material is transformed from one crystalline to another. These transitions generally have small latent heat and small volume changes than solid–liquid transitions. Solid–solid PCMs offer the

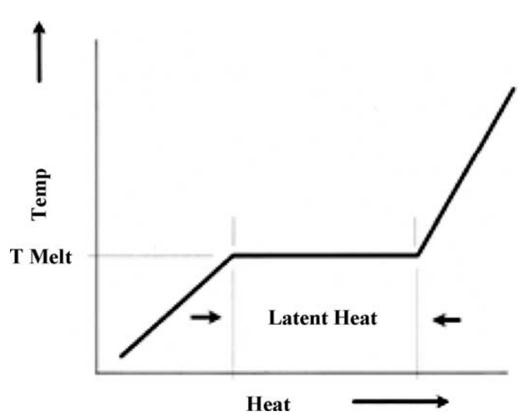

Fig. 4. Changes in temperature and heat during the change in phase. *Source*: Nuckols [16].

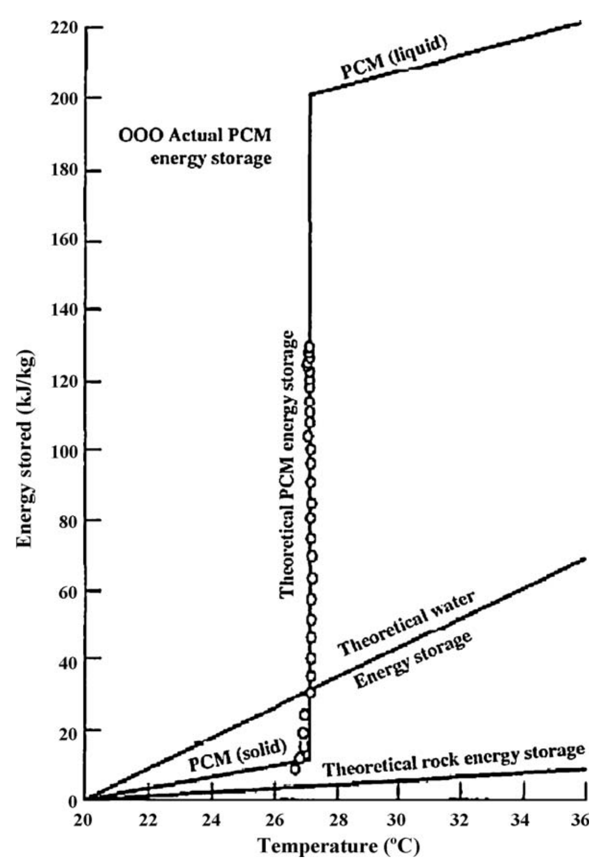

Fig. 5. Performance comparison of PCM, water and rock based storage system. *Source*: Kaygusuz [17].

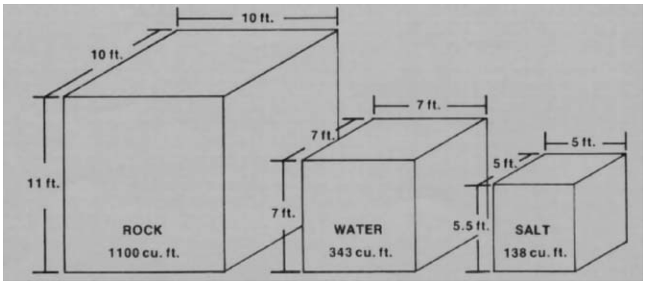

Fig. 6. Comparative volumes for the same amount of heat storage using three different storage materials.

advantages of less stringent container requirements and greater design flexibility [18]. Most promising materials are organic solid solution of pentaerythritol (m.p. 188 °C, latent heat of fusion 323 kJ/kg), pentaglycerine (m.p. 81 °C, latent heat of fusion 216 kJ/kg), Li_2SO_4 (m.p. 578 °C, latent heat of fusion 214 kJ/kg) and KHF_2 (m.p. 196 °C, latent heat of fusion 135 kJ/kg) [19].

Solid–gas and liquid–gas transition through have higher latent heat of phase transition but their large volume changes on phase transition are associated with the containment problems and rule out their potential utility in thermal-storage systems. Large changes in volume make the system complex and impractical [20]. Solid–liquid transformations have comparatively smaller latent heat than liquid–gas. However, these transformations involve only a small change (of order of 10% or less) in volume. Solid–liquid transitions have proved to be economically attractive for use in thermal energy storage systems. These are available in a range of heats of fusion and transition temperatures. PCMs themselves cannot be used as heat transfer medium. A separate heat transfer medium must me employed with heat exchanger in between to transfer energy from the source to the PCM and from PCM to the load. The heat exchanger to be used has to be designed specially, in view of the low thermal diffusivity of PCMs in general. The volume changes of the PCMs on melting would also necessitate special volume design of the containers to wholes PCM. It should be able to absorb these volume changes and should also be compatible with the PCM used. Any latent heat energy storage system therefore, possess at least following three components:

(i) A suitable PCM with its melting point in the desired temperature range.
(ii) A suitable heat exchange surface.
(iii) A suitable container compatible with the PCM.

The development of a latent heat thermal energy storage system hence, involves the understanding of three essential subjects: phase change materials, containers materials and heat exchangers. A wide range of technical options available for storing low-temperature thermal energy is shown in Fig. 7 [20].

4. Storage of latent heat in phase change materials

Phase change materials are "Latent" heat storage materials. They use chemical bonds to store and release heat. The thermal energy transfer occurs when the chemical bonds with the material break up as the PCM changes from a solid to a liquid, or from a liquid to a solid. This is called a change in state, or "phase". Initially, these solid–liquid PCMs perform like conventional storage materials; their temperature rises as they absorb heat. Unlike conventional (sensible) storage materials, when PCMs reach the temperature at which they change phase (their melting point) they absorb large amounts of heat without getting hotter. The temperature then stays constant until the melting process is finished. The heat stored during the phase change process of the material is called latent heat. The effect of latent heat storage has two main advantages: (i) it is possible to store large amounts of heat with only small temperature changes and therefore to have a high storage density. (ii) Because the change of phase at a constant temperature takes some time to complete, it becomes possible to

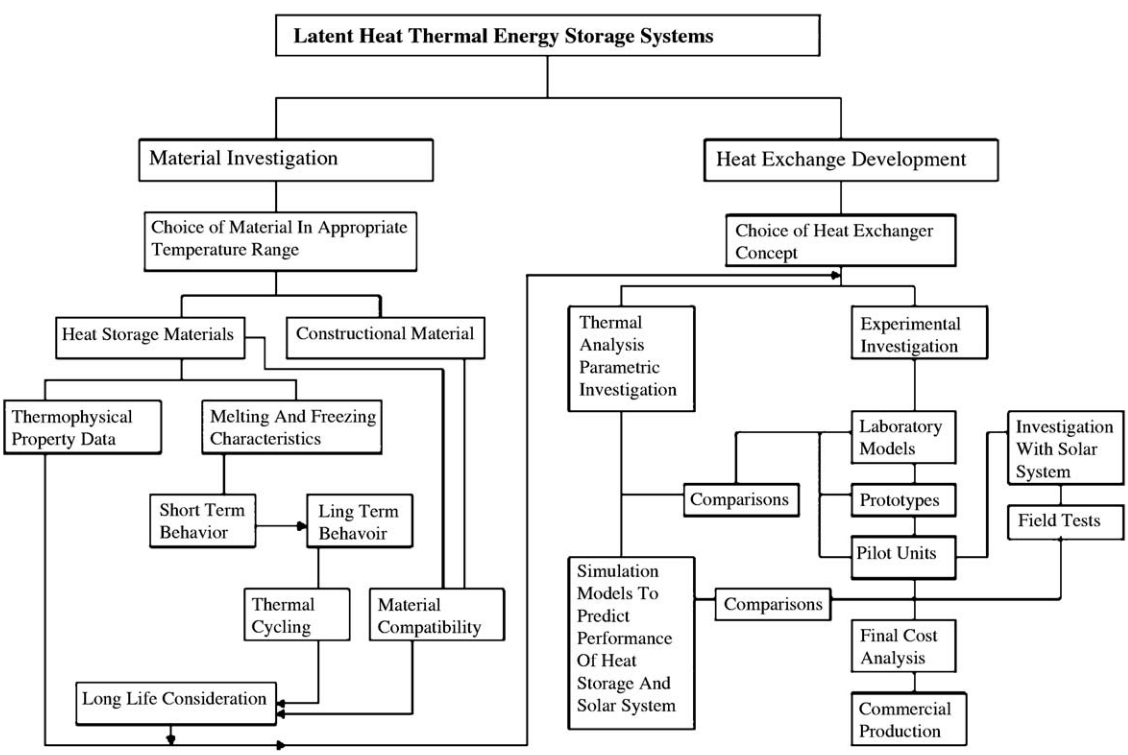

Fig. 7. Flow chart showing different stages involved in the development of latent heat storage system.

smooth temperature variations. When the ambient temperature in the space around the PCM material drops, the PCM solidifies, releasing its stored latent heat. They store 5–14 times more heat per unit volume than sensible storage materials such as water, masonry, or rock [21]. PCM take advantage of latent heat that can be stored or released from a material over a narrow temperature range. PCM possesses the ability to change their state with a certain temperature range. These materials absorb energy during the heating process as phase change takes place and release energy to the environment in the phase change range during a reverse cooling process. Basically, there are three methods of storing thermal energy: sensible, latent and thermo-chemical heat or cold storage. Thermal energy storage in solid-to-liquid phase change employing phase change materials has attracted much interest in solar systems due to the follow advantages:

(i) It involves PCMs that have high latent heat storage capacity.
(ii) The PCMs melt and solidify at a nearly constant temperature.
(iii) A small volume is required for a latent heat storage system, thereby the heat losses from the system maintains in a reasonable level during the charging and discharging of heat.

A large number of PCMs are known to melt with a heat of fusion in any required range. However, for their employment as latent heat storage materials these materials must exhibit certain desirable thermodynamic, kinetic and chemical properties. Moreover, economic considerations and large-scale easy availability of the phase change materials is also very important. The PCM to be used in the design of thermal-storage systems should possess desirable thermophysical, kinetics and chemical properties which are as follows [15,22–25].

4.1. Thermal properties

(i) *Suitable phase-transition temperature* (melting temperature) in the desired operating temperature range.
(ii) *High sensitive heat capacity and latent heat of fusion* per unit volume to minimize the physical size of the heat storage container.
(iii) *High specific heat* to provide for additional significant sensible heat storage.
(iv) *High thermal conductivity* of both solid and liquid phases to assist the charging and discharging of energy of the storage systems.

4.2. Physical properties

(i) *High density*, so that a smaller container volume holds the material.
(ii) *Small volume changes* on phase transformation.
(iii) *Low vapor pressure* at operating temperatures to reduce the containment problem.
(iv) *Congruent melting* (phase stability) of the phase change material for a constant storage capacity of the material with each freezing/melting cycle.

4.3. Kinetic properties

(i) *High nucleation rate* to avoid super cooling of the liquid phase.
(ii) High rate of crystal growth, so that the system can meet demands of heat recovery from the storage system.

4.4. Chemical properties

(i) *Long-term chemical stability*.
(ii) *Complete reversible freeze/melt cycle*.
(iii) *No degradation* after a large number of freeze/melt cycle.
(iv) *Compatibility* (non-corrosiveness) with materials of construction.
(v) *Non-toxic, non-flammable and non-explosive* materials for safety.

4.5. Economic criteria

(i) Large-scale availability.
(ii) Cost effective.

5. Classification of PCMs

A large number of phase change materials (organic, inorganic and eutectic) are available in any required temperature range from 0 to 150 °C that is interesting for solar applications. A classification of PCMs is given in Fig. 8. There are a large number of organic and inorganic chemical materials, which can be identified as PCM from

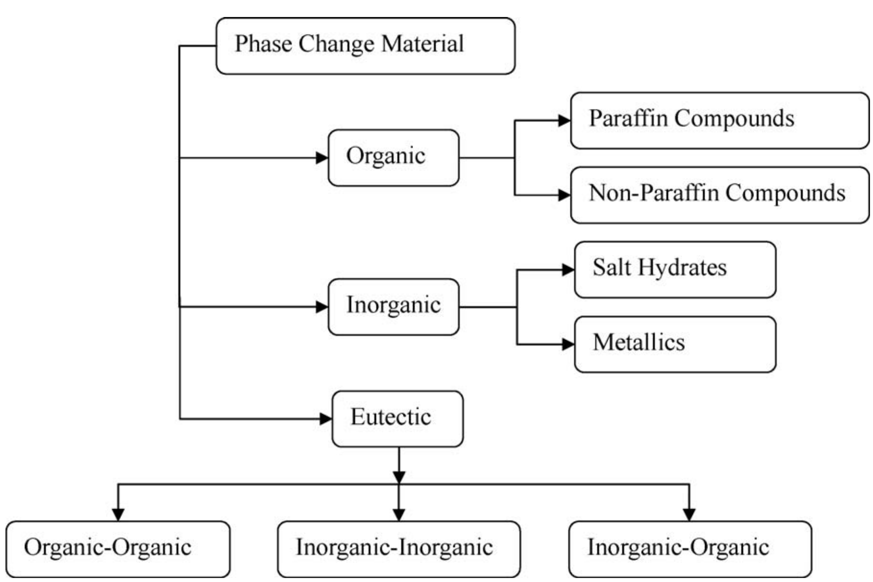

Fig. 8. Classification of PCMs.

the point of view melting temperature and latent heat of fusion. However, except for the melting point in the operating range, majority of phase change materials does not satisfy the criteria required for an adequate storage media. As no single material can have all the required properties for an ideal thermal-storage media, one has to use the available materials and try to make up for the poor physical property by an adequate system design. For example metallic fins can be used to increase the thermal conductivity of PCMs, supercooling may be suppressed by introducing a nucleating agent or a 'cold finger' in the storage material and incongruent melting can be inhibited by use of suitable thickness.

In general inorganic compounds have almost double volumetric latent heat storage capacity (250–400 kg/dm^3) than the organic compounds (128–200 kg/dm^3). For their very different thermal and chemical behavior, the properties of each subgroup which affects the design of latent heat thermal energy storage systems using PCMs of that subgroup are discussed in detail below.

5.1. Organic phase change materials

Organic materials are further described as paraffin and non-paraffins. Organic materials include congruent melting (the material should melt completely so that the liquid and solid phases are identical in composition. Otherwise, the difference in densities between solid and liquid cause segregation resulting in changes in the chemical composition of the material) means melt and freeze repeatedly without phase segregation and consequent degradation of their latent heat of fusion, self nucleation means they crystallize with little or no supercooling and usually non-corrosiveness.

5.1.1. Paraffins

Paraffin wax consists of a mixture of mostly straight chain n-alkanes CH_3–(CH_2)–CH_3. The crystallization of the (CH3)– chain release a large amount of latent heat. Both the melting point and latent heat of fusion increase with chain length. Paraffin qualifies as heat of fusion storage materials due to their availability in a large temperature range. Due to cost consideration, however, only technical grade paraffins may be used as PCMs in latent heat storage systems. Paraffin is safe, reliable, predictable, less expensive and non-corrosive. They are chemically inert and stable below 500 °C, show little volume changes on melting and have low vapor pressure in the melt form. For these properties of the paraffins, system-using paraffins usually have very long freeze–melt cycle. Table 2a lists thermal properties of some technical grade paraffins, which are essentially, paraffin mixtures and are not completely refined oil [21]. The melting point of alkane increases with the increasing number of carbon atoms. Apart from some several favorable characteristics of paraffins, such as congruent melting and good nucleating properties, they show some undesirable properties such as: (i) low thermal conductivity, (ii) non-compatibility with the plastic container and (iii) moderate flammability. All these undesirable effects can be partly eliminated by slightly modifying the wax and the storage unit. Some selected paraffins are shown in Table 2b along-with their melting point, latent heat of fusion and groups. PCMs are categorized as: (i) group I, most promising; (ii) group II, promising; and (iii) group III, less promising.

Table 2a
Thermal properties of some paraffins.

Paraffin[a]	Freezing point/range (°C)	Heat of fusion (kJ/kg)	Group[b]
6106	42–44	189	I
P116[c]	45–48	210	I
5838	48–50	189	I
6035	58–60	189	I
6403	62–64	189	I
6499	66–68	189	I

Source: Sharma et al. [15].

[a] Manufacturer of technical Grade Paraffin's 6106, 5838, 6035, 6403, and 6499: Ter Hell Paraffin Hamburg, FRG.
[b] Group I, most promising; group II, promising; group III, less promising; – insufficient data.
[c] Manufacturer of Paraffin's P116: Sun Company, USA.

Table 2b
Melting point and latent heat of fusion of paraffins.

No. of carbon atoms	Melting point (°C)	Latent heat of fusion (kJ/kg)	Group[a]
14	5.5	228	I
15	10	205	II
16	16.7	237.1	I
17	21.7	213	II
18	28.0	244	I
19	32.0	222	II
20	36.7	246	I
21	40.2	200	II
22	44.0	249	II
23	47.5	232	II
24	50.6	255	II
25	49.4	238	II
26	56.3	256	II
27	58.8	236	II
28	61.6	253	II
29	63.4	240	II
30	65.4	251	II
31	68.0	242	II
32	69.5	170	II
33	73.9	268	II
34	75.9	269	II

Source: Sharma et al. [15].

[a] Group I, most promising; and Group II, promising.

5.1.2. Non-paraffins

The non-paraffin organics are the most numerous of the phase change materials with highly varied properties. Each of these materials will have its own properties unlike the paraffins, which have very similar properties. This is the largest category of candidate's materials for phase change storage. Abhat [26] and Buddhi and Sawhney [25] have conducted an extensive survey of organic materials and identified a number of esters, fatty acids, alcohol's and glycol's suitable for energy storage. These organic materials are further subgroups as fatty acids and other non-paraffin organic. These materials are flammable and should not be exposed to excessively high temperature, flames or oxidizing agents. Few non-paraffins are tabulated in Table 3.

Some of the features of these organic materials are as follows: (i) high heat of fusion, (ii) inflammability, (iii) low thermal conductivity, (iv) low flash points, (v) varying level of toxicity, and (vi) instability at high temperatures.

Fatty acids have high heat of fusion values comparable to that of paraffins. Fatty acids also show reproducible melting and freezing behavior and freeze with no supercooling [27,28]. The general formula describing all the fatty acid is given by $CH_3(CH_2)_{2n}{\cdot}COOH$ and hence, qualify as good PCMs. Their major drawback, however, is their cost, which is 2–2.5 times greater than that of technical grade paraffins. They are also mild corrosive. Some fatty acids of low temperature latent heat storage applications are tabulated in Table 4.

5.2. Inorganic phase change materials

Inorganic materials are further classified as salt hydrate and metallics. These phase change materials do not supercool

Table 3
Melting point and latent heat of fusion of non-paraffins.

Material	Melting point (°C)	Latent heat (kJ/kg)	Group[a]
Formic acid	7.8	247	III
Caprylic acid	16.3	149	–
Glycerin	17.9	198.7	III
D-Lactic acid	26	184	I
Methyl palmitate	29	205	II
Camphenilone	39	205	II
Docosyl bromide	40	201	II
Caprylone	40	259	II
Phenol	41	120	III
Heptadecanone	41	201	II
1-Cyclohexyl Octadecane	41	218	II
4-Heptadecanone	41	197	II
p-Toluidine	43.3	167	–
Cyanamide	44	209	II
Methyl eicosanoate	45	230	II
3-Heptadecanone	48	218	II
2-Heptadecanone	48	218	II
Hydrocinnamic acid	48.0	118	–
Cetyl alcohol	49.3	141	–
α-Nepthylamine	50.0	93	–
Camphene	50	238	III
O-Nitroaniline	50.0	93	–
9-Heptadecanone	51	213	II
Thymol	51.5	115	–
Methyl behenate	52	234	II
Diphenylamine	52.9	107	–
p-Dichlorobenzene	53.1	121	–
Oxalate	54.3	178	–
Hypophosphoric acid	55	213	II
O-Xylene dichloride	55.0	121	–
β-Chloroacetic acid	56.0	147	III
Chloroacetic acid	56	130	III
Nitronaphthalene	56.7	103	–
Trimyristin	33–57	201–213	I
Heptadecanoic acid	60.6	189	II
α-Chloroacetic acid	61.2	130	–
Beeswax	61.8	177	II
Glycolic acid	63	109	–
p-Bromophenol	63.5	86	–
Azobenzene	67.1	121	–
Acrylic acid	68.0	115	–
Dinitrotoluene (2,4)	70.0	111	–
Phenylacetic acid	76.7	102	–
Thiosinamine	77.0	140	–
Bromocamphor	77	174	–
Durene	79.3	156	–
Benzylamine	78.0	174	–
Methyl bromobenzoate	81	126	–
Alpha naphthol	96	163	–
Glutaric acid	97.5	156	–
p-Xylene dichloride	100	138.7	–
Catechol	104.3	207	III
Quinone	115	171	II
Acetanilide	118.9	222	II
Succinic anhydride	119	204	II
Benzoic acid	121.7	142.8	III
Stilbene	124	167	–
Benzamide	127.2	169.4	II

Source: Sharma et al. [15].

[a] Group I, most promising; Group II, promising; Group III, less promising; and –, insufficient data.

appreciably and their heats of fusion do not degrade with cycling.

5.2.1. Salt hydrates

Salt hydrates may be regarded as alloys of inorganic salts and water forming a typical crystalline solid of general formula $AB{\cdot}nH_2O$. The solid–liquid transformation of salt hydrates is actually a dehydration of hydration of the salt, although this process resembles melting or freezing thermodynamically. A salt hydrates usually melts to either to a salt hydrate with fewer moles of water, i.e.

$$AB \cdot nH_2O \rightarrow AB \cdot mH_2O + (n-m)H_2O \quad (5)$$

or to its anhydrous form

$$AB \cdot nH_2O \rightarrow AB + nH_2O \quad (6)$$

At the melting point the hydrate crystals breakup into anhydrous salt and water, or into a lower hydrate and water. One problem with most salt hydrates is that of incongruent melting caused by the fact that the released water of crystallization is not sufficient to dissolve all the solid phase present. Due to density difference, the lower hydrate (or anhydrous salt) settles down at the bottom of the container. Most salt hydrates also have poor nucleating properties resulting in supercooling of the liquid before crystallization begins. One solution to this problem is to add a nucleating agent, which provides the nucleon for initiation of crystal formation. Another possibility is to retain some crystals, in a small cold region, to serve as nuclei. Salt hydrates are the most important group of PCMs, which have been extensively studied for their use in latent heat thermal energy storage systems. The most attractive properties of salt hydrates are: (i) high latent heat of fusion per unit volume, (ii) relatively high thermal conductivity (almost double of the paraffins), and (iii) small volume changes on melting. They are not very corrosive, compatible with plastics and only slightly toxic. Many salt hydrates are sufficiently inexpensive for the use in storage [29]. Three types of the behavior of the melted salts can be identified: congruent, incongruent and semi-congruent melting.

(i) Congruent melting occurs when the anhydrous salt is completely soluble in its water of hydration at the melting temperature.
(ii) Incongruent melting occurs when the salt is not entirely soluble in its water of hydration at the melting point.
(iii) Semi-congruent melting the liquid and solid phases in equilibrium during a phase transition is of different melting composition because of conversion of the hydrate to a lower-hydrated material through loss of water.

The major problem in using salt hydrates, as PCMs is the most of them, which are judged suitable for use in thermal storage, melts incongruently. As n moles of water of hydration are not sufficient to dissolves one mole of salt, the resulting solution is supersaturated at the melting temperature. The solid salt, due to its higher density, settles down at the bottom of the container and is

Table 4
Melting point and latent heat of fusion of fatty acids.

Material	Formula	Melting point (°C)	Latent heat (kJ/kg)	Group[a]
Acetic acid	CH_3COOH	16.7	184	I
Polyethylene glycol 600	$H(OC_2H_2)_n{\cdot}OH$	20–25	146	I
Capric acid	$CH_3(CH_2)_8{\cdot}COOH$	36	152	–
Elaidic acid	$C_8H_7C_9H_{16}{\cdot}COOH$	47	218	I
Lauric acid	$CH_3(CH_2)_{10}{\cdot}COOH$	49	178	II
Pentadecanoic acid	$CH_3(CH_2)_{13}{\cdot}COOH$	52.5	178	–
Tristearin	$(C_{17}H_{35}COO)C_3H_5$	56	191	I
Myristic acid	$CH_3(CH_2)_{12}{\cdot}COOH$	58	199	I
Palmitic acid	$CH_3(CH_2)_{14}{\cdot}COOH$	55	163	I
Stearic acid	$CH_3(CH_2)_{16}{\cdot}COOH$	69.4	199	I
Acetamide	CH_3CONH_2	81	241	I
Methyl fumarate	$(CHCO_2NH_3)_2$	102	242	I

Source: Sharma et al. [15].

[a] Group I, most promising; Group II, promising; and –, insufficient data.

unavailable for recombination with water during the reverse process of freezing. This results in an irreversible melting–freezing of the salt hydrate goes on decreasing with each charge–discharge cycle. Another important problem common to salt hydrates is that of supercooling. At the fusion temperature, the rate of nucleation is generally very low. To achieve a reasonable rate of nucleation, the solution has to be supercooled and hence energy instead of being discharged at fusion temperature is discharged at much lower temperature. Other problem faced with salt hydrates is the spontaneous of salt hydrates with lower number of water moles during the discharge process. Adding chemicals can prevent the nucleation of lower salt hydrates, which preferentially increases the solubility of lower salt hydrates over the original salt hydrates with higher number of water moles. The problem of incongruent melting can be tackled by one of the following means: (i) by mechanical stirring [29], (ii) by encapsulating the PCM to reduce separation [30], (iii) by adding of the thickening agents which prevent setting of the solid salts by holding it in suspension [31], (iv) by use of excess of water so that melted crystals do not produce supersaturated solution [32], and (v) by modifying the chemical composition of the system and making incongruent material congruent [33,34].

To overcome the problem of salt segregation and supercooling of salt hydrates, scientists of General Electric Co., NY [35] suggested a rolling cylinder heat storage system. The system consists of a cylindrical vessel mounted horizontally with two sets of rollers. A rotation rate of 3 rpm produced sufficient motion of the solid content (i) to create effective chemical equilibrium, (ii) to prevent nucleation of solid crystals on the walls, and (iii) to assume rapid attainment of axial equilibrium in long cylinders.

Some of the advantages of the rolling cylinder method as listed by [36] are: (i) complete phase change, (ii) latent heat released was in the range of 90–100% of the theoretical latent heat, (iii) repeatable performance over 200 cycles, (iv) high internal heat transfer rates, and (v) freezing occurred uniformly. A list of salt hydrates is given in Table 5.

Table 5
Melting point and latent heat of fusion of salt hydrates.

Material	Material point (°C)	Latent heat ((kJ/kg)	Group[a]
$K_2HPO_4·6H_2O$	14.0	109	II
$FeBr_3·6H_2O$	21.0	105	II
$Mn(NO_3)_2·6H_2O$	25.5	148	II
$FeBr_3·6H_2O$	27.0	105	II
$CaCl_2·12H_2O$	29.8	174	I
$LiNO_3·2H_2O$	30.0	296	I
$LiNO_3·3H_2O$	30	189	I
$Na_2CO_3·10H_2O$	32.0	267	II
$Na_2SO_4·10H_2O$	32.4	241	II
$KFe(SO_4)_2·12H_2O$	33	173	I
$CaBr_2·6H_2O$	34	138	II
$LiBr_2·2H_2O$	34	124	I
$Zn(NO_3)_2·6H_2O$	36.1	134	III
$FeCl_3·6H_2O$	37.0	223	I
$Mn(NO_3)_2·4H_2O$	37.1	115	II
$Na_2HPO_4·12H_2O$	40.0	279	II
$CaSO_4·7H_2O$	40.7	170	I
$KF·2H_2O$	42	162	III
$MgI_2·8H_2O$	42	133	III
$CaI_2·6H_2O$	42	162	III
$K_2HPO_4·7H_2O$	45.0	145	II
$Zn(NO_3)_2·4H_2O$	45	110	III
$Mg(NO_3)_2·4H_2O$	47.0	142	II
$Ca(NO_3)_2·4H_2O$	47.0	153	I
$Fe(NO_3)_2·9H_2O$	47	155	I
$Na_2SiO_3·4H_2O$	48	168	II
$K_2HPO_4·3H_2O$	48	99	II
$Na_2S_2O_3·5H_2O$	48.5	210	II
$MgSO_4·7H_2O$	48.5	202	II
$Ca(NO_3)_2·3H_2O$	51	104	I
$Zn(NO_3)_2·2H_2O$	55	68	III
$FeCl_3·2H_2O$	56	90	I
$Ni(NO_3)_2·6H_2O$	57.0	169	II
$MnCl_2·4H_2O$	58.0	151	II
$MgCl_2·4H_2O$	58.0	178	II
$CH_3COONa·3H_2O$	58.0	265	II
$Fe(NO_3)_2·6H_2O$	60.5	126	–
$NaAl(SO_4)_2·10H_2O$	61.0	181	I
$NaOH·H_2O$	64.3	273	I
$Na_3PO_4·12H_2O$	65.0	190	–
$LiCH_3COO·2H_2O$	70	150	II
$Al(NO_3)_2·9H_2O$	72	155	I
$Ba(OH)_2·8H_2O$	78	265	II
$Mg(NO_3)_2·6H_2O$	89.9	167	II
$KAl(SO_4)_2·12H_2O$	91	184	II
$MgCl_2·6H_2O$	117	167	I

Source: Sharma et al. [15].

[a] Group I, most promising; Group II, promising; Group III, less promising; and –, insufficient data.

5.2.2. Metallics

This category includes the low melting metals and metal eutectics. These metallics have not yet been seriously considered for PCM technology because of weight penalties. However, when volume is a consideration, they are likely candidates because of the high heat of fusion per unit volume. They have high thermal conductivities, so fillers with added weight penalties are not required. The use of metallics poses a number of unusual engineering problems. A major difference between the metallics and other PCMs is their high thermal conductivity. A list of some selected metallics is given in Table 6. Some of the features of these materials are as follows:

(i) Low heat of fusion per unit weight.
(ii) High heat of fusion per unit volume.
(iii) High thermal conductivity.
(iv) Low specific heat.
(v) Relatively low vapor pressure.

5.3. Eutectics

A eutectic is a minimum-melting composition of two or more components, each of which melts and freezes congruently forming a mixture of the component crystals during crystallization [37]. Eutectic nearly always melts and freezes without segregation since they freeze to an intimate mixture of crystals, leaving little opportunity for the components to separate. On melting both components liquefy simultaneously, again with separation unlikely. Some segregation PCM compositions have sometimes been incorrectly called eutectics, since they are minimum melting. Because of the components undergoes a peritectic reaction during phase transition, however, they should more properly be termed peritectics [38]. The eutectic point of laboratory grade hexadecane

Table 6
Melting point and latent heat of fusion of metallics.

Material	Melting point (°C)	Latent heat (kJ/kg)	Group[a]
Gallium–gallium antimony eutectic	29.8	–	–
Gallium	30.0	80.3	I
Cerrolow eutectic	58	90.9	–
Bi–Cd–In eutectic	61	25	–
Cerrobend eutectic	70	32.6	I
Bi–Pb–In eutectic	70	29	–
Bi–In eutectic	72	25	–
Bi–Pb–tin eutectic	96	–	–
Bi–Pb eutectic	125	–	–

Source: Sharma et al. [15].

[a] Group I, most promising; and –, insufficient data.

Table 7
List of organic and inorganic eutectics.

Material	Composition (wt.%)	Melting point (°C)	Latent heat (kJ/kg)	Group[a]
$CaCl_2{\cdot}6H_2O + CaBr_2{\cdot}6H_2O$	45 + 55	14.7	140	–
Triethylolethane + water + urea	38.5 + 31.5 + 30	13.4	160	I
$C_{14}H_{28}O_2 + C_{10}H_{20}O_2$	34 + 66	24	147.7	–
$CaCl_2 + MgCl_2{\cdot}6H_2O$	50 + 50	25	95	II
$CH_3CONH_2 + NH_2CONH_2$	50 + 50	27	163	II
Triethylolethane + urea	62.5 + 37.5	29.8	218	I
$Ca(NO_3){\cdot}4H_2O + Mg(NO_3)_3{\cdot}6H_2O$	47 + 53	30	136	–
$CH_3COONa{\cdot}3H_2O + NH_2CONH_2$	40 + 60	30	200.5	I
$NH_2CONH_2 + NH_4NO_3$	53 + 47	46	95	II
$Mg(NO_3)_3{\cdot}6H_2O + NH_4NO_3$	61.5 + 38.5	52	125.5	I
$Mg(NO_3)_3{\cdot}6H_2O + MgCl_2{\cdot}6H_2O$	58.7 + 41.3	59	132.2	I
$Mg(NO_3)_3{\cdot}6H_2O + MgCl_2{\cdot}6H_2O$	50 + 50	29.1	144	–
$Mg(NO_3)_3{\cdot}6H_2O + Al(NO_3)_2{\cdot}9H_2O$	53 + 47	61	148	–
$CH_3CONH_2 + C_{17}H_{35}COOH$	50 + 50	65	218	–
$Mg(NO_3)_3{\cdot}6H_2O + MgBr_2{\cdot}6H_2O$	59 + 41	66	168	I
Naphthalene + benzoic acid	67.1 + 32.9	67	123.4	–
$NH_2CONH_2 + NH_4Br$	66.6 + 33.4	76	151	II
$LiNO_3 + NH_4NO_3 + NaNO_3$	25 + 65 + 10	80.5	113	–
$LiNO_3 + NH_4NO_3 + KNO_3$	26.4 + 58.7 + 14.9	81.5	116	–
$LiNO_3 + NH_4NO_3 + NH_4Cl$	27 + 68 + 5	81.6	108	–

Source: Sharma et al. [15].

[a] Group I, most promising; Group II, promising; and –, insufficient data.

(m.p. 5.3 °C) and tetradecane (m.p. 17.9 °C) mixture occurs at approximately 91.67% of tetradecane, and its phase change temperature is approximately 1.7 °C. A list of eutectic is given in Table 7.

A large number of solid–liquid PCMs have been investigated for heating and cooling applications [19,24,39–44]. Recently, the incorporation of heat storage system in solar dryers has grown interest to the researcher. Heat storage system using PCM review article are available for any one application except solar dryers for drying of agricultural food products. Therefore, in this paper, an attempt has been taken to summarize the investigation of the solar drying system having sensible heat storage and latent heat storage with PCMs. This review will help to find the design, development of suitable heat storage unit for solar dryers.

6. Solar dryers with thermal heat storage materials: a review

Butler and Troeger [45] have experimentally evaluated a solar collector-cum-rockbed storage system for peanut drying. The drying time ranged from 22 to 25 h to reduce the moisture content from 20% to the safe storage moisture level with an air flow rate of 4.9 m^3/s.

Garg et al. [46] experimentally investigated inexpensive solar collector cum storage system, i.e. a solar air heater with an augmented integral rock system for agricultural uses [Fig. 9(a–c)]. For a given rock bed thickness and small value of mass flow rate, where appreciable rise of temperature above the ambient occurs, the use of two glass covers is recommended as the use of single or double glass covers depends on the compromise of optical and thermal losses. Storage in the integrated rock storage and collection system is effective normally up to 3.30 pm irrespective of mass flow rate. The performance of the system is promising showing a satisfactory overall efficiency improvement as compared either to commonly used conventional solar air heater or with the integrated rock storage and collection system.

A non-mechanical solar dryer (Fig. 10) based on convective heat and mass transfer and with energy storage has been constructed and tested to investigate the drying characteristics of various tropical products (cassava leaves, cassava chips, pepper and fish) by Ayensu and Asiedu-Bondzie [47]. The solar collector is capable of transferring 118 W m^{-2} to the drying air at a temperature of 32 °C. The drying time for solar drying of a sample is half the time taken in open-air (sun) drying. The drying process is controlled by initial removal of 'free' water followed by removal of 'bound' water. Cassava chips of length l dry according to $t = (12l + 60)$h; which predicts that for samples of negligible dimensions (e.g. rice and maize) a minimum drying period of 60 h may be required to achieve an equilibrium moisture content of 14% (wet basis) in the solar dryer. The efficiency of the solar collector is 22%, and the rock storage system stores 1.1 kWh^{-1} to enhance drying.

Tiwari et al. [48] worked on experimental simulation of a grain drying for wheat crop having sensible heat storage using rocks (average size 5–8 cm diameter, density I750 kg/ml and specific heat 0.81 kJ/kg K). The experimental observations have been used

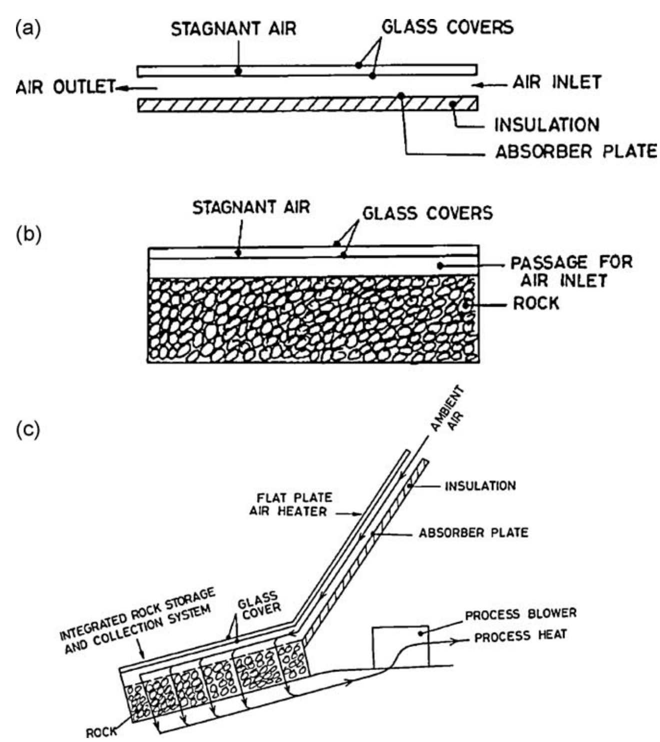

Fig. 9. (a) Flat plate air heater. (b) Integrated rock storage and collection system. (c) Augmented integrated rock system.

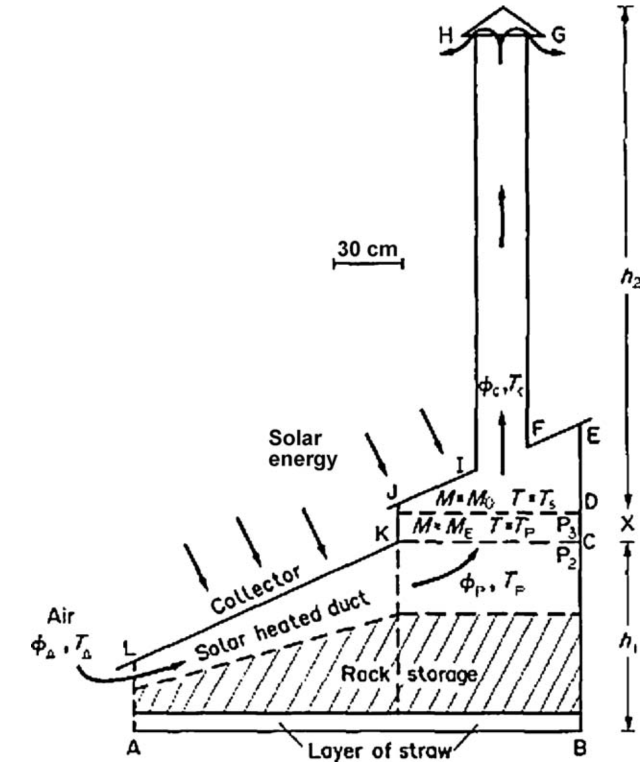

Fig. 10. Solar dryer showing drying chamber (CEJK), chimney (FGHI) and plenum chamber (ABCKL) with rock storage.

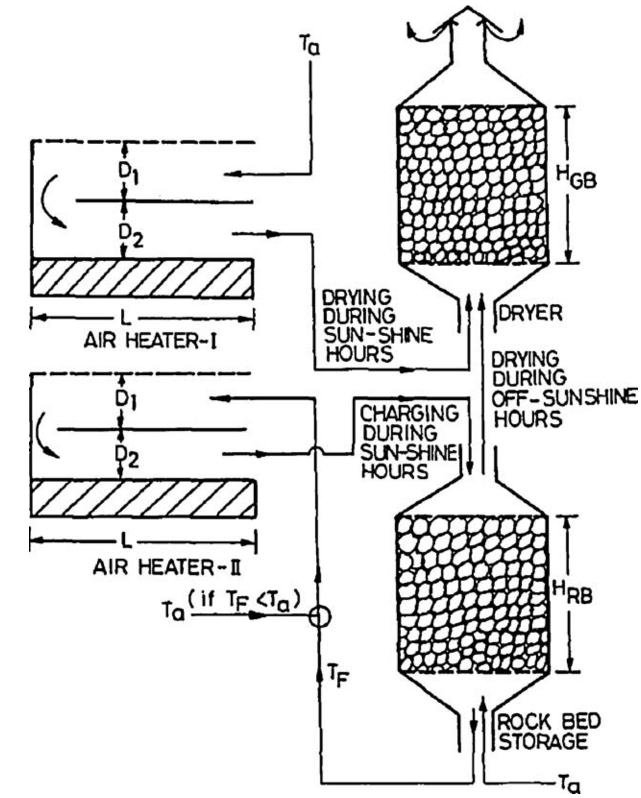

Fig. 11. Schematic view of the drying bin-cum-air-heater-cum-rockbed storage for deep-bed drying of coriander.

to evaluate the drying time for wheat crop for given moisture content. It is observed that the fluctuation in temperature is significantly reduced due to the storage effect. On the basis of experimental simulation, the following conclusions have been drawn: (1) the steady state condition for drying the wheat crop with and without thermal storage is reached after about 2 h for a given storage capacity and I kg of wheat grain (drying material), (2) the moisture content of the drying material decreases with increase in time for a given temperature, (3) the drying rate is reduced with the decrease of moisture content, (4) the steady state condition will take a larger time to achieve for high thermal capacity of the rock bed thermal storage, and (5) by using thermal storage, the maximum temperature of the drying material is reduced within a safe range, thereby improving the quality of the agricultural procedure.

Chauhan et al. [49] compared drying characteristics of coriander in a stationary 0.5 tonne/batch capacity deep-bed dryer coupled to a solar air heater and a solar air-heater-cum-rockbed storage unit to receive hot air during sunshine and off-sunshine hours, respectively (Fig. 11). The drying bed was assumed to consist of a number of thin layers of grains stacked upon each other. The theoretical investigation was made by writing the energy and mass balance equations for different components of the dryer-cum-air-heater-cum-storage and by adopting a finite difference approach for simulation. The results revealed that for reducing the moisture content from 28.2% (db) to 11.4% (db) the solar air heater takes 27 cumulative sunshine hours, i.e. about 3 sunshine days, whereas the solar air heater during sunshine hours and the rockbed storage during off-sunshine hours, combined take 31 cumulative hours (18 sunshine and 13 off-sunshine hours), i.e. about 2 days and 2 nights at an air mass velocity of 250 kg/hm^2. During sunshine drying, the effect of grain bed depths on drying performance of coriander is observed to be remarkable, while the air mass velocity has no significant effect on the moisture content reduction rate. However, off-sunshine drying time can be reduced by 1 h for each increment of 50 kg/h m^2 in air mass velocity, i.e. the drying time can be set at 14 off-sunshine hours for an air flow velocity of 200 kg/h m^2 and 12 off-sunshine hours for an air flow velocity of 300 kg/h m^2. Hence, the heat stored in the rockbed can be used effectively for heating the inlet (ambient) air for off-sunshine drying of agricultural products.

Ayensu [50] designed a solar drying system [Fig. 12(a, b)] having rock storage system on the principles of convective heat flow. The dryer was constructed from local materials (wood, metals and glass sheets) and used to dry food crops (cassava, pepper, okro, groundnuts, etc.). The solar collector could transfer 118 W m^{-2} thermal power to the drying air. Ambient air at 32 °C and 80% relative humidity (RH) could be heated to 45 °C at 40% RH for drying. The crops were dried to a final moisture content of $<$14% (wet basis) and were preserved for a period of 1 year without deterioration. The low-temperature drying system ensured the viability of the seeds for planting. The drying process can be represented by an empirical equation of the form $M(t) = M_0 \exp(-kt)$ or $dM/dt = -kM$, where M_0 is the initial moisture content, $M(t)$ is the moisture content at time t, and k is the drying constant. Under identical conditions, a high value of k was correlated with a shorter drying period. The drying process takes place in two phases: constant rate and falling rate periods, and the drying equation was solved to predict the total drying time. The mechanisms for the dehydration are the removal of unbound "free" water in the cell cavities and of "bound" water (water films) trapped within cells or chemically bound with solids as water of crystallization. It took nearly 2 times longer to dehydrate crops by open-air sun-drying compared to the solar dryer.

Devahastin et al. [51] proposed via numerical simulation the use of latent heat storage to store energy from the exhausted gas of a modified spouted bed grain dryer and saving energy up to 15%.

Ziegler et al. [52] analyzed sorption storage of solar heat using a layer of wheat as the desiccant by means of a deep-bed drying

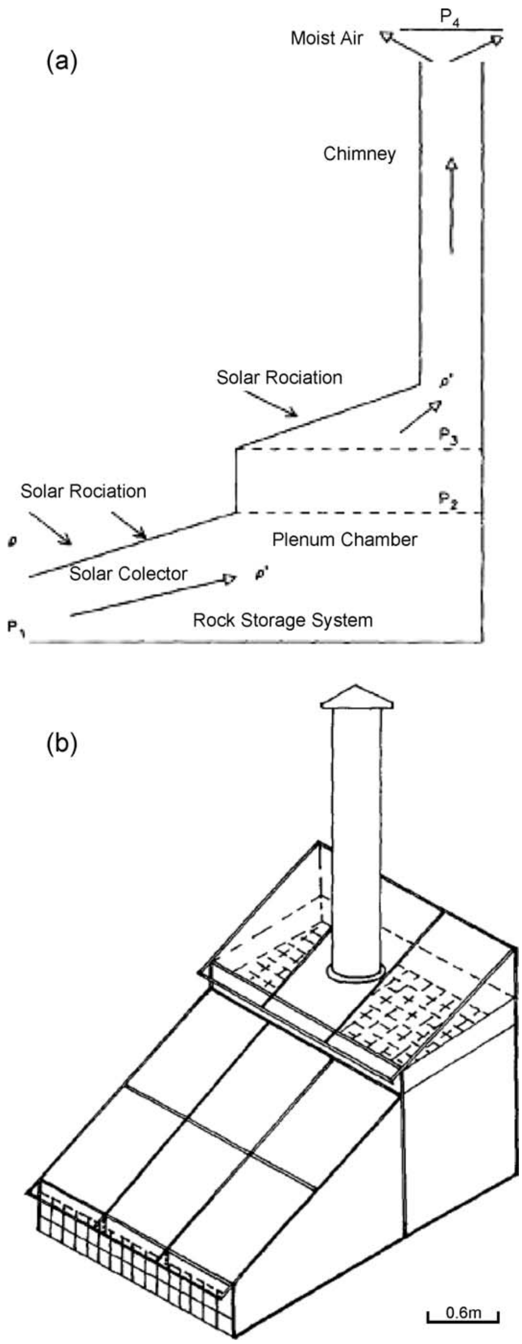

Fig. 12. (a) Schematic diagram of fixed bed dryer with solar collector, plenum chamber, drying chamber and chimney. (b) General view of the dryer.

model (Fig. 13). Sorption storage of solar drying potential offers a promising possibility for gentle, uninterrupted in-storage drying of different agricultural bulk materials such as grain, hay or wood chips without combustion of fossil fuels. The use of grain as the desiccant has decisive economic and processing advantages compared with, e.g. Silica Gel. Grain is not endangered by dust. The required strategy of control is based on the mixing of ambient air and solar heated air that has also flown though the desiccant bulk. A relative humidity of the drying air of 65% can be maintained day and night except for those hours when the relative humidity of ambient air is below 65%. Mold growth inside the storage is avoided as a matter of principle. The required regeneration temperatures can he easily achieved using simple collectors that are operated temporarily in a low-flow mode. At typical climatic

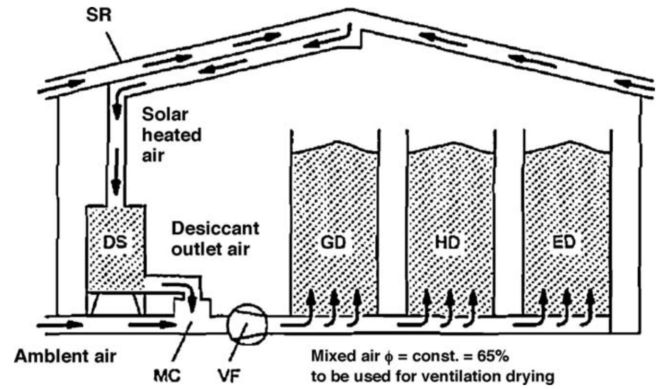

Fig. 13. Multiple use of solar roof and desiccant storage for tandem-arranged drying processes (schematic): SR: solar roof, DS: desiccant storage, MC: mixing chamber, VF: ventilation fan, GD: grain drying, HD: hay drying, ED: energy crops drying.

conditions in East Germany, a collector area of about 5 m^2 per m^2 ventilated area is sufficient to avoid economic losses due to over drying and to reduce the danger of decay to a minimum even at unfavorable weather conditions. The holding container of the desiccant grain may be constructed similar to conventional mixed flow dryers and alternatively be operated in continuous-flow. Due to its airflow resistance, such storage of solar drying potential is mainly suitable for ventilation drying of bulk materials. The comparatively small mass of the desiccant grain which temporarily can be exposed to collector-outlet temperatures of more than 80 °C may be used as animal feed after the drying period. The economic efficiency of the whole process will considerably depend on the multiple use of the collector-storage-unit for the tandem-arranged drying processes. Intended to be applied to solar-assisted in-storage drying of agricultural bulk materials, the probability of the persistence of unfavorable weather periods was quantified statistically for Potsdam for the month of August, as an example. Simulation results demonstrate that a relative humidity of the drying air of 65% can be maintained day and night for weeks without combustion of fossil fuels. Using a simple strategy of control, periods with insufficient solar radiation can be bridged over. Simple solar air heaters can be used to avoid economic losses due to over drying and to reduce the danger of decay to a minimum even at unfavorable climatic conditions.

Aboul-Enein et al. [9] reported a parametric study of a solar air heater with and without thermal storage for solar drying applications (Fig. 14). Three kinds of material for thermal storage were used, i.e. water, stones and sand. The average temperature of flowing air increases with the increase of the collector length and width up to typical values for these parameters. The outlet temperature of flowing air was found to decrease with an increase of the airflow channel spacing and mass flow rate. The thermal performance of the air heater with sensible storage materials is

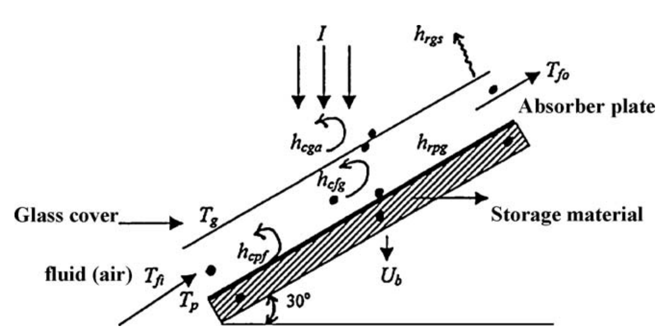

Fig. 14. Schematic view of the air heater.

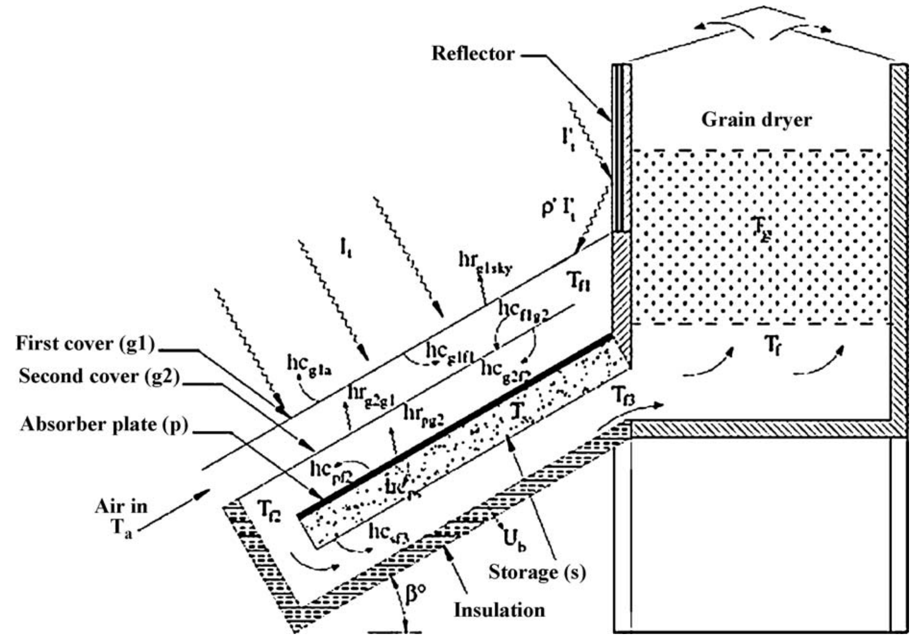

Fig. 15. Inclined multi-pass air heater with in-built thermal storage attached with deep-bed drying system.

considerably higher than that without the storage. An optimal thickness of the storage material of about 0.12 m was found to be convenient for drying various agriculture products. In addition, the proposed mathematical model may be used for estimating of the thermal performance of flat plate solar air heater with and without thermal storage.

Jain and Jain [53] evaluated performance of a tilted multi-pass solar air heater with in-built thermal storage and attached with the deep-bed dryer for drying the paddy crop using an appropriate deep-bed drying model (Fig. 15). The grain temperature increases with the increase of collector length, breadth and tilt angle up to typical value of these parameters. The thermal energy storage also affect during the off-sunshine hours is very pertinent for crop-drying applications. The proposed mathematical model is useful for evaluating the thermal performance of a flat plate solar air heater for the grain drying applications. It is also useful to predict the moisture content, grain temperature, humidity of drying air and drying rate in the grain bed.

Jain [54] studied a periodical analysis of multi-tray crop drying attached to an inclined multi-pass solar air heater with in-built thermal storage for drying of the paddy crop (Fig. 16). The crop temperature increases with the increase in collector length, breadth and tilt angle up to typical value of these parameters. The thin layer drying equation has been used to study the drying rate and hourly reduction in moisture content in the different trays. It has been observed that the crop moisture content decreases with the drying time of the day. Different drying rate has been observed in different drying trays due to the variation in

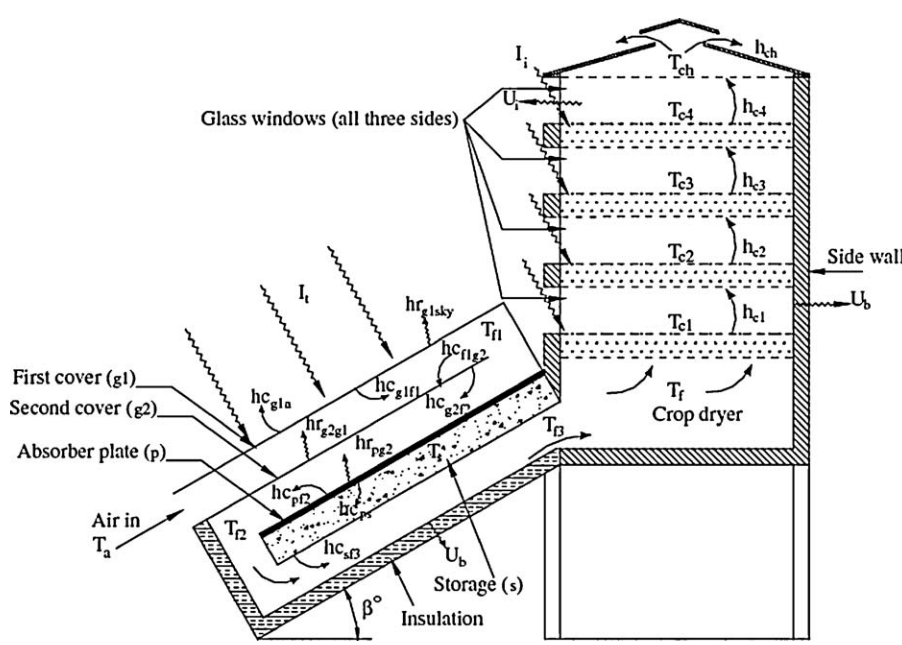

Fig. 16. Multi-tray crop dryer with inclined multi-pass air heater with in-built thermal storage.

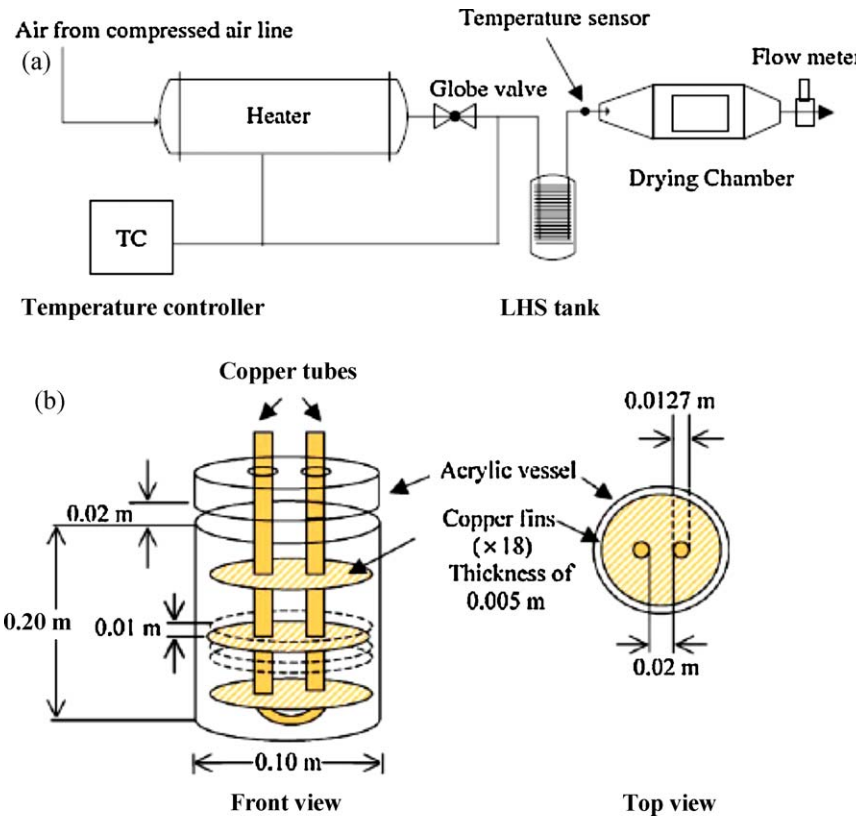

Fig. 17. (a) Schematic diagram of the experiment set-up with attached drying chamber. (b) A detailed sketch of the LHS vessel.

crop temperatures. The thermal efficiency of the drying increases with increase in mass of the crop.

Devahastin and Pitaksuriyarat [55] investigated the feasibility of using latent heat storage with paraffin wax [Fig. 17(a, b)] as a phase change material to conserve excess solar energy during drying and release it when the energy availability is inadequate or not available and its effect on drying kinetics of a food product (sweet potato). Heat transfer characteristics, temperature profiles as well as the effects of the inlet air temperature and velocity on the charge and discharge periods were investigated. It was found that melting was dominated by heat conduction followed by free convection; melting took place from the center of the LHS to a point far away in the radial direction and took place from top to bottom points in the axial direction. However, only heat conduction was dominant in the solidification process. PCM froze from an outer to an inner of the LHS tank due to heat loss to the surrounding. Charge time decreased with an increase of the inlet air temperature and air velocity. The amount of extractable energy per unit mass flow rate of inlet ambient air was 1920 and 1386 kJ min kg^{-1} when using inlet air velocity of 1 and 2 ms^{-1}, respectively. This LHS could save thermal energy during drying of sweet potato by approximately 40% and 34% when using inlet air velocity of 1 and 2 ms^{-1}, respectively.

Jain [56] presented a transient analytical model to study the new concept of a solar crop dryer having reversed absorber plate type collector and thermal storage with natural airflow (Fig. 18). The performance of this crop dryer with packed bed was carried out for drying onions in trays. The crop temperature depends on width of the air flowing channel and height of packed bed. The thermal energy storage affects drying during the non-sunshine hours and is very pertinent in reducing the fluctuation in temperature for drying. The proposed mathematical model is useful for evaluating the performance of reversed absorber type collector and thermal storage with natural convective solar crop dryer. It is also useful for predicting the crop temperature, moisture content and drying rate of the crop.

Madhlopa and Ngwalo [57] designed, constructed and evaluated an indirect type natural convection solar dryer with integrated collector-storage solar and biomass-backup heaters for drying of

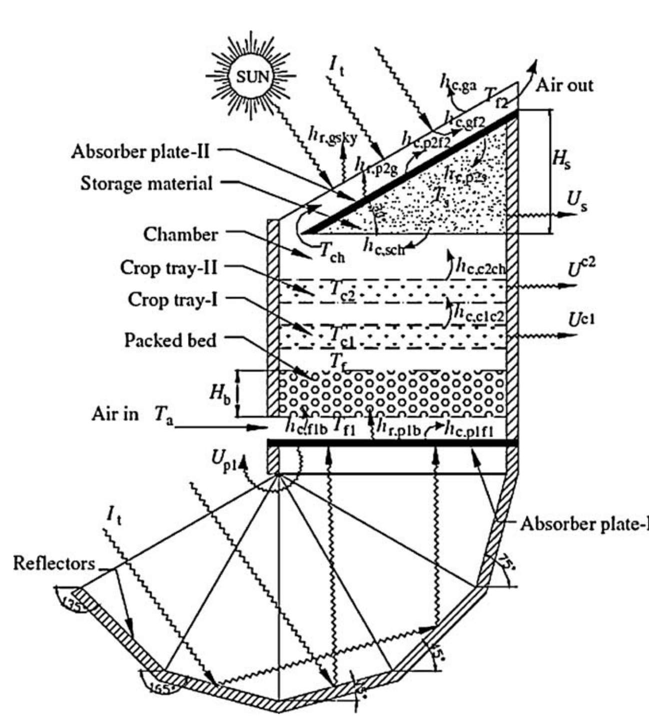

Fig. 18. Schematic view of reversed absorber with thermal storage natural convective solar crop dryer.

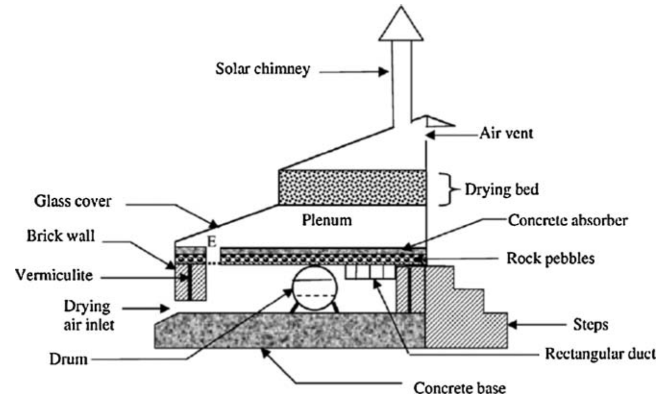

Fig. 19. Cross-sectional view of the solar dryer through the burner, collector, drying chamber and solar chimney.

fresh pineapple (*Ananas comosus*). The major components of the dryer are biomass burner (with a rectangular duct and flue gas chimney), collector-storage thermal mass and drying chamber (with a conventional solar chimney) are shown in Fig. 19. The thermal mass was placed in the top part of the biomass burner enclosure, stored part of the heat from both solar and biomass air heaters, thereby moderating temperature fluctuations in the drying chamber and reducing wastage of energy. It was possible to dry a batch of pineapples using solar energy only on clear days. In this operational mode, the dryer reduced the moisture content of pineapple slices from about 669–11% (db) final moisture content which is within acceptable limits for safe storage and yielded a nutritious dried product. The solar mode of operation was slowest in drying the samples, with the solar–biomass mode being fastest under the prevailing meteorological conditions. Drying proceeded successfully even under very bad weather conditions in the solar–biomass mode of operation. The rate of drying was not uniform across the trays. Consequently, there is need for interchanging them during drying to achieve a uniformly dried product. Reverse thermo-siphoning was observed in the solar chimney during nocturnal drying, which reveals the need to re-visit the design of solar chimneys fitted on solar dryers developed for both diurnal and nocturnal free-convection drying of crops.

Shanmugam and Natarajan [58] investigated the performance of an indirect forced convection and desiccant integrated solar dryer [Fig. 20(a, b)] for drying of green peas and pineapple slices with and without the reflective mirror. The system is operated in two modes, sunshine hours and off-sunshine hours. During sunshine hours the hot air from the flat plate collector is forced to the drying chamber for drying the product and simultaneously the desiccant bed receives solar radiation directly and through the reflected mirror. In the off-sunshine hours, the dryer is operated by circulating the air inside the drying chamber through the desiccant bed by a reversible fan. The inclusion of reflective mirror on the desiccant bed increases the drying potential by 20%. The useful temperature rise of about 10 °C was achieved with mirror, which reduced the drying time by 2 and 4 h for green peas and pineapple, respectively. Also, the pick-up efficiency, drying rate and average dryer thermal efficiency were relatively higher, when compared to solar drying and desiccant integrated drying. Uniform drying in all the trays were achieved with good quality in terms of colour and microbiological decay, when compared to solar drying. Taste of the dried pineapple is satisfactory. The desiccant material is stable even after continuous operation for more than a year. The dryer can be used for drying various agricultural products. It can reduce drying time and improve quality of the dried product.

A new type of solar dryer (Fig. 21), i.e. in-built thermal-storage agro solar dryer, was conceived, mathematically modelled,

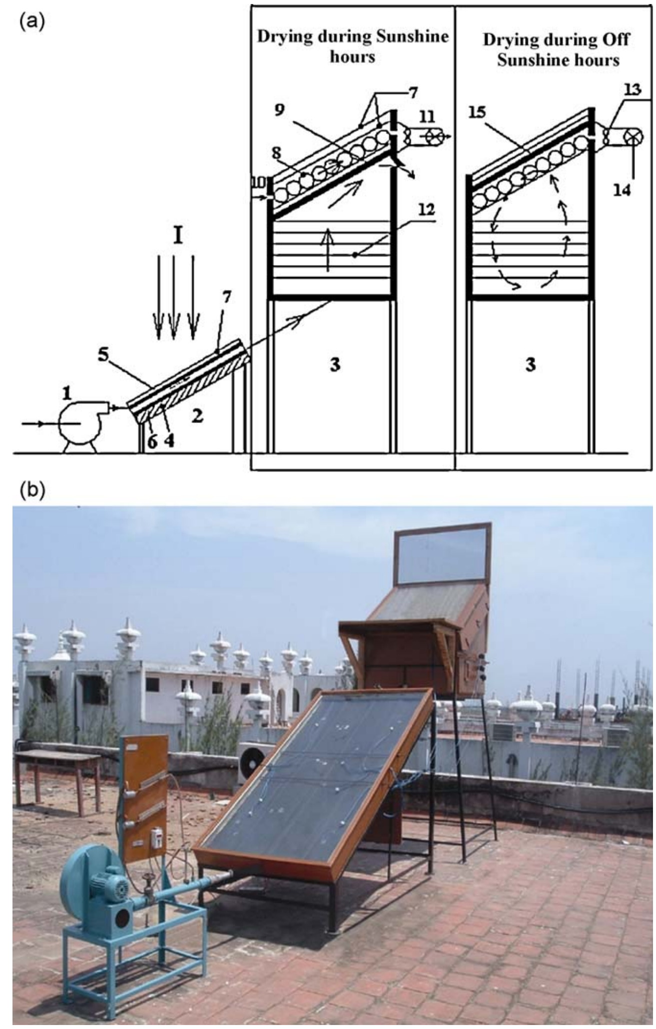

Fig. 20. (a) Schematic of the desiccant integrated solar dryer. 1. Blower, 2. Flat plate solar air collector, 3. Drying chamber, 4. Insulation, 5. Absorber plate, 6. Bottom plate, 7. Transparent cover, 8. Desiccant bed, 9. Plywood, 10. Air inlet, 11. Duct for air exit, 12. Drying trays, 13. Reversible fan, 14. Valve, 15. Plywood. (b) Pictorial view of the experimental set-up.

designed, simulated, developed and investigated experimentally for agricultural products such as chillies and fenugreek leaves by Potdukhe and Thombre [59]. Thermic oil was used as a storage material for reducing the drying period and enhancing the quality of dried products. The novel absorber utilizing thermic fluid as in-built storage had helped to attain higher drying air temperatures in the drying chamber around 65 ± 3 °C with the length of absorber as 0.826 m. It can maintain uniform drying air temperature for longer period, which is a noteworthy feature of dryer non-existent in the natural convection solar dryers. The length of operation of solar dryer is increased by 1–2 h depending on the solar radiation on the particular day. This will ensure higher drying rate without damage to agricultural products. This also exhibits excellent control over the airflow rate and the drying rates by the dryer. The model developed can be used to optimize absorber plate for any size of solar dryer. It can also predict the temperatures at various locations without the need for experimentation on the prototype. This was the first attempt in the development of comprehensive analytical model that has yielded best results. The drying efficiency of the new type of solar dryer for chillies is 21%, which is higher than reported. The collection efficiency of the new type of solar dryer for chillies is 34%, which is also higher than reported. Higher percentage weight reduction occurred for the first tray in all the tests. Higher percentage weight

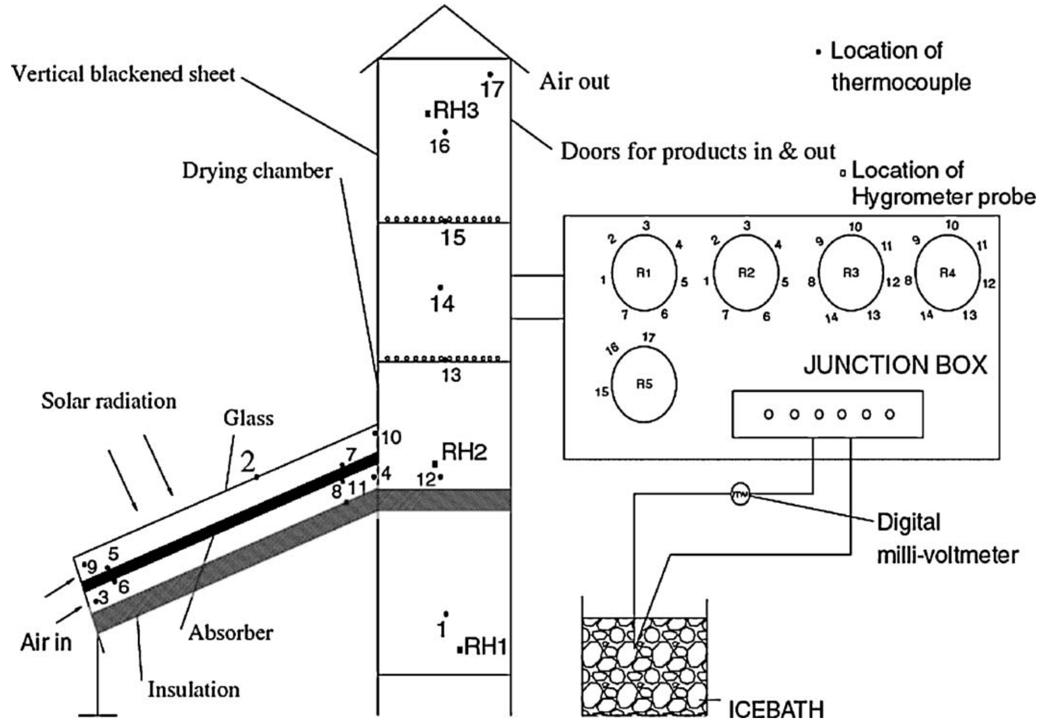

Fig. 21. Schematic of experimental set-up.

reduction (47.3%) occurred when the spacing between the two trays was 46 cm. The drying period in the solar dryer was reduced by 75 and 40% compared with open-sun drying and using conventional dryer, respectively. The colour value of dried chillies powder from the new type of solar dryer has been considerably high, about 4 times compared with the open-sun drying sample. The striking feature of the dryer is that all parts were detachable and were built with locally available materials and skills. The dryer is most suitable for agricultural products that are sensitive to direct exposure to solar radiation such as chillies, fenugreek leaves, onion, grapes, sweet potatoes and mint. No external power is required for operating the solar dryer since it operates on the combined effect of thermal buoyancy and chimney. Hence, the maintenance and operating costs for such dryer are negligible. So this drier provides desired drying air temperature for a longer period. The length of operation of the solar air heater and the efficiency of the dryer were increased, and better quality of agricultural products in terms of colour value were obtained compared with open-sun drying.

7. Conclusion

The above discussion emphasizes the fact that the advantages and drawbacks of various designs of solar dryer having heat storage systems for drying of agricultural food products. As drying energy plays an important role in sustainable energy management in Indian as well as worldwide, effective utilization of solar energy holds the key to future's non-exhaustive energy source thereby reduce the time between energy supply and energy demand. A great deal of experimental work over the last few decades has already demonstrated for drying of agricultural food products using solar dryer having solar thermal energy storage in the form of sensible heat storage and Latent heat storage. Heat storage using 'phase change materials' is a wise alternative. The main applications for PCMs are when space restrictions limit larger thermal-storage units in solar drying systems. The effective thermal energy storage technology in solar dryers for drying of agricultural food products is an area where available information should be consolidated and missing information needs to be obtained through further research.

8. Future vision

There is need to focus on the hybrid solar drying with thermal storage (latent heat storage and sensible heat storage) for continuous drying of agricultural/food products at steady and moderate temperature of 40–75 °C. As only using wax as latent heat storage material qualifies as energy storage materials but a major drawback of paraffins is the low thermal conductivity. This problem is addressed through an increase of the surface area of heat transfer between the heat transfer fluid (HTF) and the PCM. The use of finned tubes as well as metal fiber and metal matrix or sand, for example, resulted in an increase of one-to five fold of the effective thermal conductivity of the PCM and hence the rate of heat transfer. Also using bamboo in solar dryer may reduce cost as it has good thermal insulation and mechanical strength compared to metal. Furthermore heat loss is a main problem of the back panel of solar dryer can be corrected by adding a coating of polyurethane foam or PU foam and dry grass stems. So, this research gap also needs adequate attention in future studies.

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